Evaluation of hydrological models for scenario analyses: signal-to-noise-ratio between scenario effects and model uncertainty

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Abstract. Many model applications suffer from the fact that although it is well known that model application implies different sources of uncertainty there is no objective criterion to decide whether a model is suitable for a particular application or not. This paper introduces a comparative index between the uncertainty of a model and the change effects of scenario calculations which enables the modeller to objectively decide about suitability of a model to be applied in scenario analysis studies. The index is called "signal-to-noise-ratio", and it is applied for an exemplary scenario study which was performed within the GLOWA-IMPETUS project in Benin. The conceptual UHP model was applied on the upper Ouémé basin. Although model calibration and validation were successful, uncertainties on model parameters and input data could be identified. Applying the "signal-to-noise-ratio" on regional scale subcatchments of the upper Ouémé comparing water availability indicators for uncertainty studies and scenario analyses the UHP model turned out to be suitable to predict long-term water balances under the present poor data availability and changing environmental conditions in subhumid West Africa.

1 Introduction

The background of this study was the assumption that ongoing global environmental change has a significant impact on the water cycle of regional scale catchments in many parts of the world. A lot of research projects such as the projects within the GLOWA programme of the German ministry of education and research, BMBF (GLOWA = global change of the water cycle, GLOWA, 2005) investigated the global change impact on regional scale hydrological systems. The GLOWA projects investigate basin scale water related effects of global change in regional river catchments on three continents: Europe, Africa and Near East. The focus thereby lies on the prediction of future changes with respect to hydrological quantities. The GLOWA-IMPETUS project focuses on the prediction of water availability in Benin (West Africa). Predicting future water fluxes under changing environmental conditions requires the use of hydrological models fed by changing boundary conditions and input data representing climate change, a change of the society and a change of the environment. These changes can be described by a set of realistic scenarios of possible future developments of a region.

To assess the hydrological consequences these changes need to be translated by hydrological models into changes in hydrological quantities (e.g. annual water budget). Due to the limited data availability in developing West African countries models have to be used which are able to calculate the catchment water fluxes right based on poor input data (information on soils, topography, weather, etc.). The catchments of interest are poorly gauged basins, and therefore also the model predictions are assumed to be uncertain. If sophisticated, process based model concepts are used, they can only be parameterised and driven with significant parameter and data uncertainty due to lacking input data. If conceptual models are used, then the simplified model structures may cause a large uncertainty of the model results. Thus the final question arises whether the used model is suitable with respect to the aim of the study and the target quantities of the model calculations.

In order to answer this question of model suitability this study looked for an objective index which directly compares the uncertainty caused by data availability and/or model parameters to the calculated effects of the scenarios. This index shall enable an assessment of the suitability of the model concept in addition to standard quality measures (e.g. model efficiency according to Nash and Suttcliffe (1970), coefficient of determination, etc.) and standard procedures analysing "only" the model uncertainty (e.g. Monte-Carlo simulations, GLUE-method after Beven and Binley, 1992).

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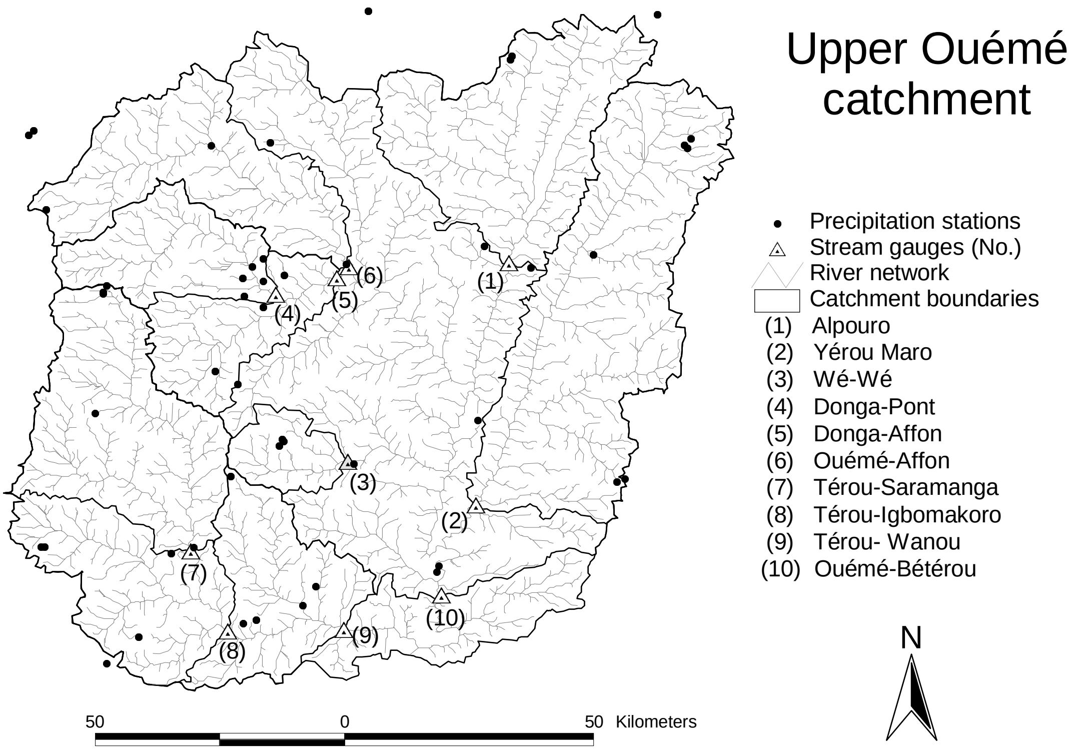

Fig. 1. Subcatchments, drainage network and stream gauges in the upper Ouémé catchment (central Benin).

2 Signal-to-noise-ratio

In general within case studies, scenario calculations and model uncertainty are discussed and evaluated separately. However the model used for scenario calculations is not free from uncertainties, and therefore a direct relation between both quantifications is necessary. If the uncertainty analysis of a model reveals a high uncertainty, then also calculated scenario effects may be caused by model artefacts. And if a model reveals almost no uncertainty in a particular case then also small scenario effects can be reliable and significant.

Based on the fact that the evaluation of the uncertainty of a model is often a result of an individual and subjective rating, a ratio between uncertainty and scenario effects is proposed here which directly and objectively links both, quantification of model uncertainty and scenario effects. It enables the comparison of total model uncertainty to the effects of integrative scenarios (combination of different changing influencing factors) as well as the comparison of particular uncertainty sources to the effects of single parts of scenarios. The "signal-to-noise-ratio" (*SNR*) is defined by Eq. (1) for measurable values:

$$SNR = \left[\frac{\frac{|X_{\text{reference}} - X_{\text{scenario}}|}{X_{\text{reference}}}}{\frac{1}{n}\sum_{i=1}^{n} \frac{|X_{\text{observed}} - X_{i,\text{uncertain}}|}{X_{\text{observed}}}} \right] - 1 \tag{1}$$

Where *SNR* = signal-to-noise ratio, $X_{\text{reference}}$ = value of the reference scenario, X_{scenario} = value of the scenario, X_{observed} = observed value, $X_{i,\text{uncertain}}$ = value of the n realisations of the uncertainty analysis, i = control variable.

Values can be water balance terms and state indicators. As only measurable indicators can be selected for calculation of *SNR* following Eq. (1), and measurable indicators are often scarce in regional scale poorly gauged basins (e.g. annual stream flow volume), a second signal-to-noise-index called SNR_{ref} is defined by Eq. (2) where the observed values in the denominator of Eq. (1) are replaced by the values of the reference simulation. Using this index SNR_{ref}, also non-measurable values can be used for comparison of model uncertainty and scenario effects (e.g. regional scale actual evapotranspiration, regional scale soil moisture deficit):

$$SNR_{\text{ref}} = \left[\frac{\frac{|X_{\text{reference}} - X_{\text{scenario}}|}{X_{\text{reference}}}}{\frac{1}{n}\sum_{i=1}^{n} \frac{|X_{\text{reference}} - X_{i,\text{uncertain}}|}{X_{\text{reference}}}} \right] - 1 \tag{2}$$

SNR and SNR_{ref} indices should be interpreted as follows: positive *SNR* values indicate that scenario effects are larger than model uncertainty effects. Values lager than 1 (scenario effect at least doubles model uncertainty) are called high *SNR* values and demonstrate a sufficient suitability of a model for a given case study. Negative *SNR* values imply that a model is not suitable for scenario analysis in the particular case.

Table 1. Regional scale data availability in Benin: time series (weather and stream flow data) and spatial information (Soil and geological map, vegetation classification, topographic map).

Data set	Regional resolution: Upper Ouémé basin (14 000 km^2, 1993–2000/01)
Soil	1:200 000
Topography	1:200 000
Land use	30 m (Landsat based)
Geology	1:200 000
Weather data	3-hourly to daily (1 station)
Rainfall	Daily sums (43 stations)
Stream flow	Daily discharges (11 gauges)

3 Exemplary study – UHP model application in Benin

This study is being performed on the upper Ouémé basin in central Benin. The upper Ouémé basin (Fig. 1) has a size of approx. 14 000 km^2 and shows a subhumid climate characterized by a unimodal rainy season. The mean annual precipitation amount is about 1100 mm/a, falling between April and October. The vegetation cover mainly consists of tree savannah whereas especially in the northern part savannah vegetation is replaced by agricultural land. Crusted and lateritic soils are characteristic for the region, causing a significant portion of lateral flow components, surface runoff and interflow. Groundwater recharge only takes places locally where preferential flow paths exist.

For regional model application only regionally available data can be used. The data availability in the upper Ouémé basin is presented by Table 1. Although the data availability is above-average for West African conditions and all general data sets are available, they do not suffice for process based hydrological modelling. For example soil data do not include spatially distributed soil textures or soil physical parameters, and rainfall data are resolved only in daily resolution, rainfall intensities are almost not available. Therefore a conceptual and lumped model concept (UHP model) has been selected to reproduce the long-term water fluxes and the water balance of the upper Ouémé region. The UHP model is based on four storages representing interception, root zone, soil and groundwater storages. The main process descriptions are given by Bormann and Diekkrüger (2004).

Calibration of the UHP model was performed manually for the Térou subcatchment (3133 km^2, gauge (9) in Fig. 1) for the 1993–1999 time period by maximising the model efficiency according to Nash and Suttcliffe (1970). Besides model efficiency the quality assessment focused on the long-term water balance, on the coefficient of determination and on the recession curve in the end of the rainy season. For the calibration period model efficiency was 0.75 for weekly stream flow, r^2 was 0.82 and the difference of the long-term stream flow concerning cumulative stream flow was smaller than 1% (0.1%).

The validation of the UHP model was firstly realised by a split sample test of the data available for the Térou river. For the validation period (year 2000) the same simulation quality was observed (model efficiency=0.76). Secondly the UHP model was applied on 6 neighboured regional scale subcatchments within the upper Ouémé (580 to 10 300 km^2) without a recalibration (years 1997/1998–2000). The quality assessment of the validation procedure revealed comparable model efficiencies compared to the calibration period and water balance deviations below ±10% which was defined to be acceptable. Details on the quality measures of calibration and validation procedure for the different catchments are given by Bormann and Diekkrüger (2004).

Simulation results for the entire upper Ouémé basin (sum of gauges Térou-Wanou and Ouémé-Bétérou) which represents the target scale of the IMPETUS project are shown in Fig. 2. Quality measures of this simulation are a model efficiency of 0.74, an r^2 of 0.84 (with y=1.105*x) and a deviation between measured and simulated water balance of 5.3%.

4 Model applications – uncertainties and scenarios

The aim of the hydrological investigations in Benin was the calculation of environmental change scenarios to assess possible changes in the future water availability of the upper Ouémé basin. To evaluate the predictions for possible future developments a detailed analysis of the model performance in addition to "classical" model validation is required. The most important uncertainty sources identified for the upper Ouémé basin are model parameter and input data uncertainty. Bormann and Diekkrüger (2003) tried to quantify the uncertainty of the model concept. They came to the conclusion that process based regional scale hydrological models cannot be applied in the target basin due to data constraints while the application of the conceptual UHP model only leads to small deviations between simulated and observed stream flow. In contrast on local scale process based models can be successfully applied if additional data on the catchment properties are available (Bormann et al., 2005; Giertz, 2004).

Dominant uncertainties in the upper Ouémé basin are information on rainfall distribution (in time and space) and soil properties. Precipitation shows a very high spatial and temporal variability due to different, partly small scale rainfall generation mechanisms (e.g. squall lines, local thunder storms, monsoonal rainfall). This high rainfall variability cannot be detected exhaustively by the existing, limited rain

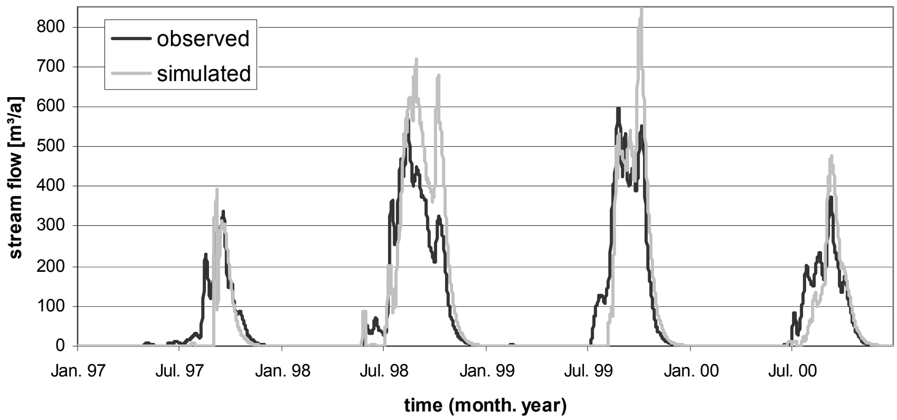

Fig. 2. Simulation results of the upper Ouémé river (14 000 km^2, result of superposition of the observed and simulated hydrographs of the stream gauges Ouémé-Bétérou and Térou-Wanou).

gauge network (43 rain gauges on 14 000 km^2), whereas the rain gauge network underlies frequent malfunctions. The investigation of a decreasing number of rainfall data on the simulation results revealed an increasing uncertainty on discharge volume with decreasing number of rainfall stations. Using the in average available density of rain gauges implied an uncertainty of about 10% with regard to annual stream flow. Furthermore the method how to derive catchment rainfall from point station data was investigated. Different methods were applied and compared (e.g. Thiessen polygons, arithmetic mean). While significant effects on single runoff events could be identified the effect on annual stream flow and therefore also on the long-term water balance was relatively small (about 5%). The analysis of model parameter uncertainty focused on the parameters representing the soil properties (e.g. soil water storage capacity, curve numbers, initial abstraction). The Monte-Carlo-method based investigation revealed a parameter uncertainty comparable in quantity to uncertainty of rainfall input into the model. The effect on annual stream flow was about 9%. Details on the uncertainty analysis are presented by Bormann and Diekkrüger (2004).

Based on regional to global scale future predictions of the Intergovernmental Panel on Climate Change (IPCC, 2001) on climate change and based on local to regional scale investigations on soil degradation in the upper Ouémé region (Junge, 2004), a set of scenarios was defined. For the time scale of 2020 scenarios of rainfall decrease and soil degradation and of a combination of both effects were described and calculated (Bormann, 2005). Three scenarios only focusing on one changing factor and one scenario combining two factors are:

– “rain-1”: This scenario shows a decrease in rainfall by 10%, whereas each rainfall event is reduced by 10%. This scenario implies decreasing rainfall intensities and a constant duration of the rainy season.

– “rain-2”: This scenario is characterised by a decrease of rainfall by 10%, whereas the rainfall amounts of the events stay constant, but the rainy season is shortened by the last 10%. This scenario implies a shorter rainy season but constant rainfall intensities.

– “degradation”: This scenario describes the degradation of the land surface by intensification and increase of agriculturally used areas and therefore intensified erosion (decrease of soil storage, increase of curve number, decrease of leaf area index).

– “Combination scenario”: This scenario summarises the changes assumed by scenario “rain-2” and “degradation”. Observations show that “rain-2” is more likely than “rain-1”, and therefore “rain-2” is combined with a land degradation scenario assuming an ongoing business as usual with respect to the extension of agricultural area, cutting down of tropical wood and the ensuing soil erosion.

Details on derivation and definition of the environmental scenarios with respect to changes in single components as well as in combinations are presented by Bormann (2005).

To evaluate the simulation results the definition of state indicators is necessary. These indicators are needed to assess the severity of changes in an objective manner. They of course should show significance with respect to the main target of the study (water availability in the upper Ouémé basin). Furthermore – if possible – they should be measurable to be able to set the scenario effects in relation to quantifiable uncertainty components. In this study the following indicators were used:

– Annual / long-term stream flow volume (indicator for changes in the water balance).

– Annual ETA (indicator for changes in water balance and plant productivity, but difficult to observe at regional scale).

Table 2. Signal-to-noise-ratios for three different target quantities (VOLUME = annual stream flow volumes, RUNOFF = number of days per year with stream flow >10 m^3/s, SOIL = number of days per year with soil water storage >40%).

Scenario-uncertainty combination	SNR/SNR_{ref} [-] (VOLUME)	SNR/SNR_{ref} [-] (RUNOFF)	SNR_{ref} [-] (SOIL)
Land degradation scenario (Degradation) vs. parameter uncertainty	1.12/1.35	−0.19/−0.16	1.15
Shortening of rainy season (Rain-2) vs. consideration of rainfall variability	0.28/0.85	2.65/2.28	2.88
Shortening of rainy season (Rain-2) vs. calculation of areal rainfall	1.25/1.30	0.29/1.19	26.13
Reduction of all rain events (Rain-1) vs. consideration of rainfall variability	2.64/4.27	5.18/4.56	1.34
Reduction of all rain events (Rain-1) vs. calculation of areal rainfall	5.42/5.54	1.18/2.70	15.37

– Annual number of days with stream flow (indicator for water availability in the rivers, but error-prone indicator in the subhumid tropics due to measurement errors, e.g. if water stands in the river bed but is not flowing); alternatively: days with stream flow exceeding a threshold (e.g. 1 m^3/s or 5 m^3/s).

– Days with soil moisture exceeding a threshold concerning the charge of the soil water storage (indicator for length of growing season; can be observed at point scale, but difficult to measure at regional scale).

Hydrological effects of these scenarios were calculated for three subcatchments of the upper Ouémé river: Térou-Wanou (3133 km^2), Ouémé-Affon (1165 km^2) and Donga-Affon (1329 km^2). Simulated results on changing hydrological processes were comparable for the three catchments. A decrease in rainfall input (scenarios rain-1 / rain-2) leads to decreasing evapotranspiration (−4.4%/−8.7%), decreasing stream flow (−35.3%/−12.4%) and decreasing plant available water (−10 days/−18 days above a threshold on soil water content), whereas the land surface degradation leads to an increase in stream flow (+19.5%). The combination scenario leads to an increasing stream flow (+7.3%), a decrease in evapotranspiration (−11.1%) and a dramatic decrease in soil available water (−6 to −7 weeks over a threshold on soil water content). For details on the results of the scenarios on the catchment hydrology see Bormann (2005).

5 Application of the signal-to-noise-ratio to the Térou basin

The application of the "signal-to-noise-ratio" indices (*SNR* and SNR_{ref}) on the three following water availability indicators

1. long-term stream flow volume,

2. number of days per year when stream flow exceeds 10 m^3/s and

3. number of days per year when root zone water storage exceeds 40% of storage capacity

for the Térou catchment in central Benin reveals following results for the UHP model which are summarised in Table 2. In general – according the *SNR* indices defined – the UHP model is suitable to be used for the calculation of environmental change scenarios in central Benin. All water availability indicators are meaningful with regard to questions of water availability. Except one case (comparison of the degradation scenario vs. model parameter uncertainty for the number of stream flow days) all *SNR* indices are positive, and except three cases the indices exceed the value 1 and therefore are called high *SNR* values indicating a sufficient model suitability.

The application of the SNR_{ref} index mostly leads to slightly increased values compared to *SNR* which is caused by the increase of model uncertainty in case of comparison to measurements instead of the reference simulation. If the reference simulation is used particular uncertainty sources are not regarded (e.g. measurement errors) or slightly underestimated. But the differences between *SNR* and SNR_{ref} are small. Thus also (on the catchment scale) non-measurable water availability indicators such as the "length of the time period with sufficient available water in the root zone" can be used as indicator.

The two different rainfall scenarios lead to different *SNR* indices caused by different scenario effects. But the two scenarios also have different probabilities as meteorologists rather expect a shorter rainy season instead of decreasing rainfall intensities in the subhumid tropics of West Africa. This fact needs to be considered for the rating of *SNR* results (Table 2)

Finally, attention should be drawn on the fact that the scenarios which underlie case studies such as this investigation must be as realistic and plausible as possible. Applying indices comparable to *SNR* defined in this paper may lead to the temptation to alter scenarios in a way producing high *SNR* values instead of spending intensive work in reducing model uncertainty by improving the model concept or the input data quality. This – of course – would be absolutely undesirable and would disqualify the approach to provide a subjective indicator for model suitability.

6 Conclusions

An index called signal-to-noise-ratio has been presented which can be used for objective evaluation of model suitability for scenario analysis depending on the detected uncertainty related to a particular case study. A high index indicates a large signal (scenario effect) compared to the noise (relatively small uncertainty). Thus in addition to partly subjective assessment of results of uncertainty analyses an objective index is now available. It requires the use of specific indicators (depending on the aim of the study, e.g. water availability indicators for the GLOWA-IMPETUS project) and an objective function to evaluate models for a particular application. Guaranteeing a careful definition of scenarios the model evaluation can be done based on an intensive analysis of model uncertainty.

With regard to the case study presented in this paper, the conceptual UHP model used is suitable for calculation of scenario effects in central Benin based on a poor data base. Only one of 15 *SNR* values is negative indicating a low suitability, 14 of 15 values are positive and 12 of 15 indicators indicate a sufficient suitability. These results support the successful validation of the UHP model for the upper Ouémé valley and the suitability of the conceptual model for scenario analysis under the assumption that scenarios are based on well-founded investigations and are defined in a realistic and plausible manner.

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